Final Technical Report: "Simulation of Extreme Arctic Cyclones in IPCC AR5 Experiments"

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GOALS

The primary goals of this project were to assess the ability of the current generation of global climate models (GCMs) to simulate extreme Arctic cyclones and identify changes in the characteristics of these storms caused by greenhouse-forced climate change to present.

OBJECTIVES

These goals were achieved through investigation of the following questions:

(1) What are the spatial and seasonal characteristics of extreme Arctic cyclones?

(2) How well do state-of-the-art GCMs simulate them?

(3) Are extreme Arctic cyclones already showing a response to greenhouse forcing?

APPROACH

These questions were addressed through a retrospective analysis of the transient 20th century simulations (spanning years 1850-2005) among the GCMs participating in the latest Coupled Model Intercomparison Project (CMIP5) with extra attention paid to the Community Climate System Model (CCSM4). The study used 14 GCMs with widely varying horizontal and vertical resolutions and physics packages. These simulations were compared with an atmospheric reanalysis data set covering almost this entire period (1871-2008) from NOAA's Earth System Research Laboratory: the 20th Century Reanalysis, version 2, available at www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2. This data set is described in detail by Compo et al. (2010) and provides various atmospheric fields, including sea level pressure (SLP), on daily and sub-daily time scales at 2° horizontal resolution. A higher-resolution and more reliable data set for the more recent 1979-period, NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA), was used to evaluate the climate models more rigorously. In addition, I analyzed the

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CCSM4 model's response to much stronger greenhouse forcing during its 21st-century simulation.

Extreme cyclones were defined as occurrences of daily mean SLP at least 40 hPa below the climatological annual-average SLP at a grid point. As such, no cyclone-tracking algorithm was employed, because the purpose here is to identify instances of extremely strong storms, regardless of origin or propagation. The assumption is that potential damage from polar cyclones is strongly dependent on their central pressure; therefore it is important to identify all cases when the SLP falls to extremely low values, whether that occurs from separate storms during their one-day peak intensity or from a single storm throughout its multi-day evolution. By identifying extreme cyclones in relative terms, on the basis of a deviation from the local climatological SLP, this method accounts for the large spatial variation in normal pressure patterns across high latitudes, such as the much lower (higher) background SLP around the Icelandic and Aleutian Lows (Beaufort High). Although the choice of a 40 hPa anomaly is arbitrary, it is consistent with the magnitude of SLP perturbation used to identify extreme cyclones in Chang et al. (2012) and the results of the present study are not highly sensitive to the precise value, nor to whether this anomaly threshold is expressed instead in terms of a local standard deviation of SLP. Pressure anomalies of this magnitude were found to be associated with clearly identifiable cyclones with strong pressure gradients, as expected from such deep central SLP. While extreme cyclones in the central Arctic are of primary interest in this study, the analysis domain extended to 50°N to include the climatological domain of the sub-polar Aleutian and Icelandic lows.

RESULTS

1. CCSM4 generates a significant increase in the strength and frequency of extreme Arctic cyclones in its 21st century simulation (2005-2100), with a maximum signal during autumn (Vavrus et al., 2011).

2. However, this same model does not show a strengthening of the most extreme Arctic cyclones during the 1850-2005 period, nor a significant change in their frequency.

3. The 20th Century Reanalysis does indicate a strengthening of the most extreme Arctic cyclones during similar time period (1871-2008), but most of this change occurs before 1920, when the data quality is questionable. The same conclusion generally holds for the reanalyzed frequencies of extreme cyclones, but this data set suggests noticeably higher occurrences in the high Arctic (poleward of 70°N) during the past 25 years.

4. CCSM4 produces more extreme polar cyclones than the Reanalysis, consistent with its bias toward low sea level pressure in the Arctic during almost every month (de Boer et al., 2011).

5. The CCSM4 simulations show an important shift in the location of extreme Arctic cyclones as a function of greenhouse warming (Figure 1). By the late 21st century, the model indicates a change in the location of these storms, such that they emerge in the

interior Arctic Ocean, especially over regions where sea ice loss exposes open water. However, this change is not effected by the modest greenhouse warming between 1850-2000, when the sea ice margin is further south and may act as a barrier for the production or migration of such extreme events.

6. On the whole, the GCMs in the CMIP5 collection do a reasonable job of reproducing the frequency of the strongest cyclones in the Arctic during the recent past (1979-2005), although there is a considerable amount of intermodel spread (Figure 2). Averaged among all models, there is a 15% underestimate in the occurrence of extreme Arctic cyclones compared with MERRA.

7. The favored regions for these storms are within the climatological Icelandic and Aleutian Lows, and extreme cyclones reaching the Arctic Ocean occur almost exclusively as extensions from the Icelandic Low storm track, rather than from the Aleutian Low track (Figure 3). Simulated and observed intense Arctic cyclones are primarily marine phenomena, such that maximum frequencies occur over water, especially ice-free seas. Compared with the MERRA Reanalysis, the CMIP5 models under-simulate extreme cyclones in the core sub-polar low regions and over-simulate them in the interior Arctic.

8. The models correctly simulate that the most intense Arctic cyclones are primarily a wintertime phenomenon and almost never occur during summer, but the CMIP5 models have a bias of producing too many such storms during the spring and too few during autumn (Figure 4).

9. The CMIP5 models simulate a decrease in mean annual Arctic sea level pressure since 1850, consistent with expectations from greenhouse forcing, but the trend in extreme cyclone frequency is most pronounced in the vicinity of the Aleutian and Icelandic Lows, rather than over the Arctic Ocean (Figure 5). However, a general upward trend is apparent over most of the marine Arctic, even though not all of these increases are statistically significant. In summary, I find equivocal trends in simulated mean SLP and extreme Arctic cyclones since 1850.

10. Interestingly, there is no significant correlation between extreme cyclone frequency and either horizontal model grid spacing ($r = -0.25$) or the number of vertical model layers ($r = 0.26$). There is also no significant correlation of model resolution with simulated annual-mean SLP, mean minimum daily SLP, or absolute minimum SLP. Apparently, sea level pressure biases in the models and the simulation of intense storms are affected more by internal physical processes, rather than resolution. However, the coarseness of models generally prevents representation of mesoscale polar lows, whose average diameter is around 400 km (Carleton 1996).

FUTURE WORK

The primary goal of this retrospective analysis was to identify the simulated characteristics of extreme Arctic cyclones in state-of-the-art GCMs, rather than to diagnose the underlying physical mechanisms. An important next step is to identify projected changes in these events through a prospective analysis of the CMIP5 21st-century simulations and to determine the physical drivers that might be responsible for altered characteristics of Arctic cyclones in a warming climate.

IMPACTS

These results have implications for navigation, economic activities, military operations, and coastal erosion. Existing Naval operations in the Arctic Ocean and adjacent seas can be adversely affected by the passage of extreme cyclones, and future operations will likely become even more sensitive to these weather systems if reduced ice cover promotes more Naval activities and enhanced storminess in the region. The study by Overeem et al. (2011) documents accelerating rates of coastal erosion in permafrost bluffs along the Beaufort Sea, due to storm-generated waves coinciding with expanding areas of open water. Presumably, this erosion will worsen with time as sea ice recedes and storms intensify.

RELATED PROJECTS

This topic is related to an NSF-funded collaborative project with Jennifer Francis at Rutgers University: "The Role of Arctic Amplification in Modifying Mid-latitude Atmospheric Circulation and Promoting Extreme Weather Events."

PRESENTATIONS

Oral presentation at the Community Earth System Model (CESM) Annual Workshop, June 2012: "Simulation of extreme Arctic cyclones in IPCC AR5 experiments", Breckenridge, CO.

Oral presentation at the AGU Fall Meeting, December 2012: "Simulation of extreme Arctic cyclones in IPCC AR5 experiments", San Francisco, CA.

Poster presentation at the World Climate Research Program (WCRP) Open Science Conference, October 2011: "Simulation of extreme Arctic cyclones in IPCC AR5 experiments", Denver, CO.

PUBLICATIONS

Vavrus, S., 2013: Extreme Arctic cyclones in CMIP5 historical simulations. *Geophysical Research Letters.*, 40, 6208-6212.

BROADER IMPACTS

The timeliness and outcomes of this research generated considerable interest in the media and scientific circles. A summary of highlighted features is listed below.

Science Daily and Science Newsline ("Increase in Arctic cyclones is linked to climate change"), < http://www.sciencedaily.com/releases/2014/02/140218100707.htm>

Scientific American ("Warming Arctic spurs cyclones and sea ice loss"), < http://www.scientificamerican.com/article/warming-arctic-spurs-cyclones-and-sea-ice-loss/?&WT.mc_id=SA_DD_20140220>

Nelson Institute of Environmental Studies at University of Wisconsin feature ("More extreme Arctic cyclones a symptom of climate change, new research suggests"), < http://www.nelson.wisc.edu/news/story.php?story=1850>

Expert assessment provided on 2012 Arctic "megacyclone" for NASA Earth Observatory < http://earthobservatory.nasa.gov/IOTD/view.php?id=78808>

EOS Research Spotlight, volume 95 (10), page 92 ("Climate models show increasing Arctic cyclone activity")

Wiley press release: < http://www.wiley.com/WileyCDA/PressRelease/pressReleaseId-110301.html>

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Overeem, I., R. S. Anderson, C. W. Wobus, G. D. Clow, F. E. Urban, and N. Matell, 2011: Sea ice loss enhances wave action at the Arctic coast. Geophys. Res. Lett., 38, L17503, doi:10.1029/2011GL048681.

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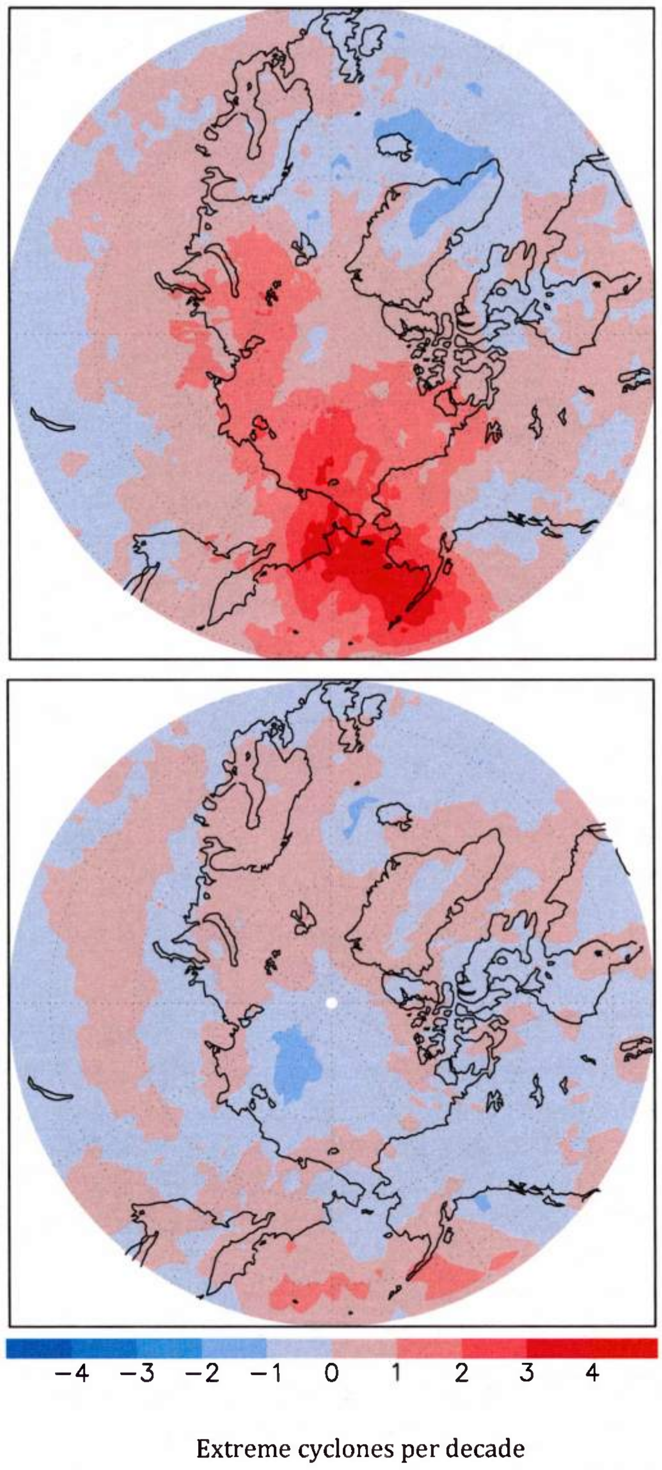

Figure 1. Linear trend in extreme cyclone frequency per decade simulated by CCSM4 during (top) 2005-2100 and (bottom) 1850-2005 in the RCP8.5 forcing scenario.

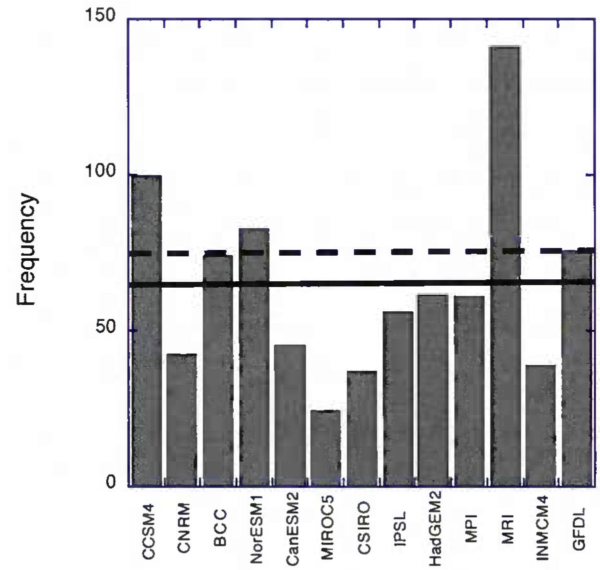

Figure 2. Number of days per year with extreme cyclones in the CMIP5 Historical simulations (1979-2005). Extreme cyclones are defined as occurrences of daily mean SLP at least 40 hPa below the annual average SLP at a grid point. The multi-model average frequency (64.4) is denoted by the solid line and the MERRA average (75.8) by the dashed line.

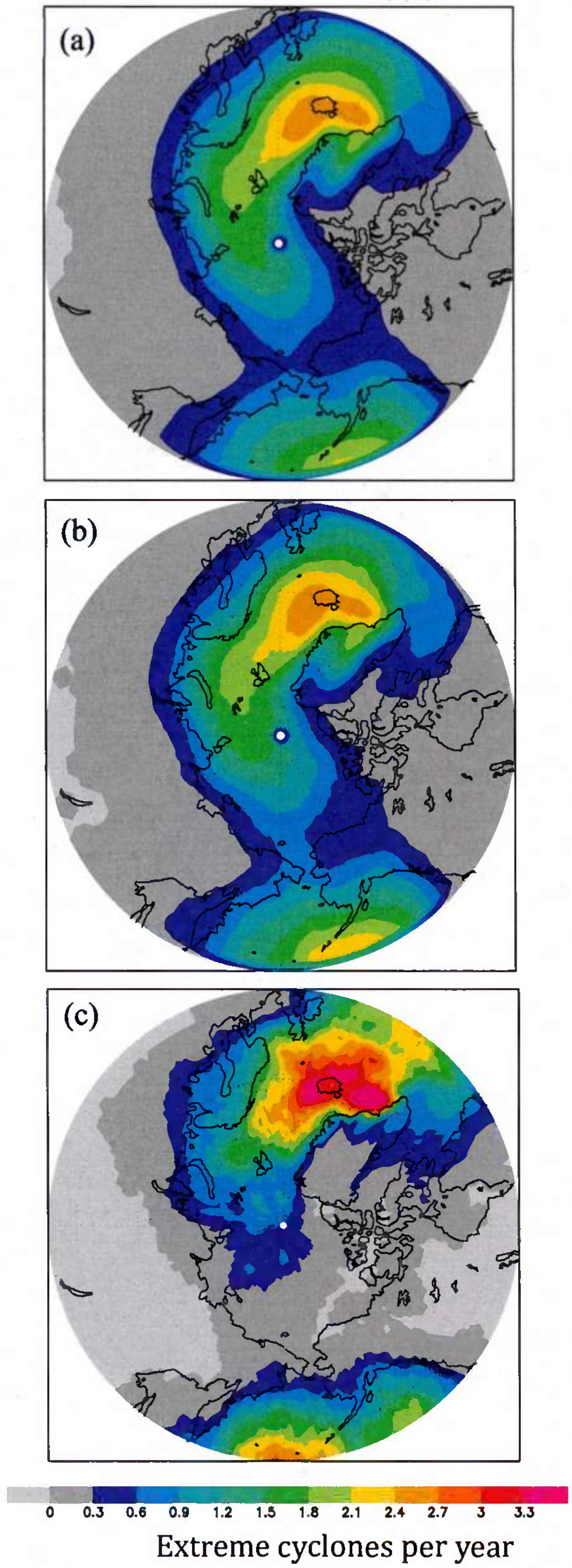

Figure 3. Average number of extreme cyclones per year in (a) CMIP5 1850-2005, (b) CMIP5 1979-2005, (c) MERRA 1979-2005.

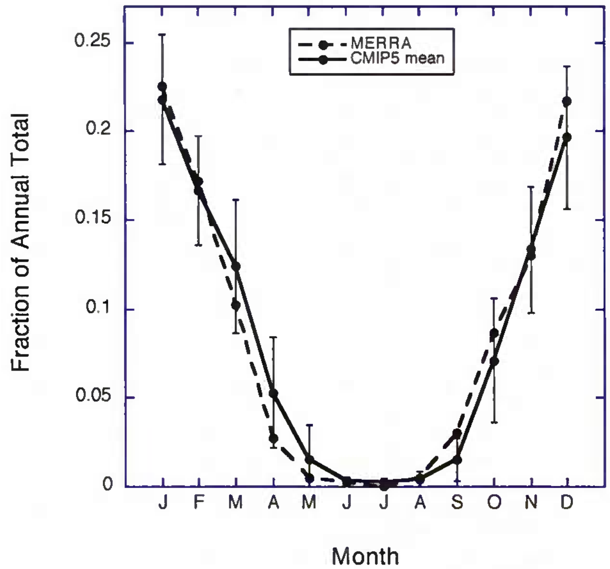

Figure 4. Annual cycle of extreme Arctic cyclones in the MERRA reanalysis (dashed) and the CMIP5 average (solid) with intermodel standard deviation depicted with whiskers. The time period of both data sets is 1979-2005.

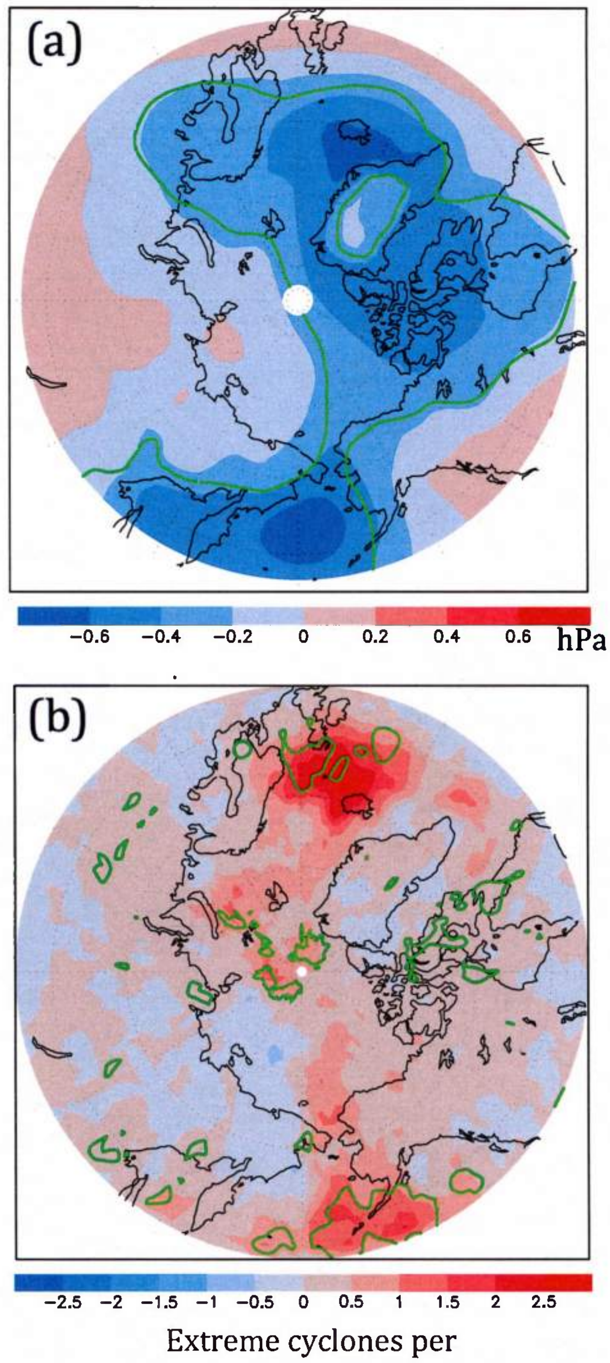

Figure 5. (a) Linear trend in mean annual SLP (hPa) from 1850 to 2005 expressed as the multi-model average (shaded) with contours of the 90% significance level, based on a two-sided student t-test using the intermodel standard deviation of trends. (b) Same but for extreme cyclone frequency trend per decade.

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14. ABSTRACT

Increasing attention is being paid to extreme weather, including recent high-profile events involving very destructive cyclones. In summer 2012 a historically powerful cyclone traversed the Arctic, a region experiencing rapid warming and dramatic loss of ice and snow cover. This project addresses whether such powerful storms are an emerging expression of anthropogenic climate change by investigating simulated extreme Arctic cyclones during the historical period (1850-2005) among global climate models in the CMIP5 archive. These GCMs are able to simulate extreme pressures associated with strong polar storms without a significant dependence on model resolution. The models display realism by generating extreme Arctic storms primarily around sub-polar cyclone regions (Aleutian and Icelandic) and preferentially during winter. Simulated secular trends in Arctic mean sea level pressure (SLP) and extreme cyclones are equivocal; both indicate increasing storminess in some regions, but the magnitude of changes to date are modest compared with future projections.

15. SUBJECT TERMS
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